Force-Velocity Relationship in three Different Variations of Prone Row Exercises

Loturco, Irineu ; Suchomel, Timothy ; Kobal, Ronaldo ; Arruda, Ademir F S ; Guerriero, Aristide ; Pereira, Lucas A ; Pai, Chi Nan

Abstract: This study examined the force-velocity relationship and tested the possibility of determining the relative loading intensity (% 1RM) in three different variations of prone row exercises. Thirty male top-level athletes from two different sports (National Team rugby union players and professional mixed martial arts fighters) were submitted to maximum dynamic strength assessments in the free prone bench pull, bent over barbell row, and bent over Smith-machine row, following standard procedures encompassing lifts performed from 40 to 100% of 1RM. The mean velocity, mean propulsive velocity, and peak velocity were measured in all attempts. Linear regression analyses were performed to establish the relationships between the different measures of bar-velocities and %1RM. The actual (obtained during the assessments) and predicted 1RM values (based on the predictive equations) for each exercise were compared using a paired t-test. In all exercises, the predicted 1RM scores - based on all velocity variables- were not different from their respective actual values. The close linear relationships between bar-velocities and distinct %1RM (coefficient of determination 80%, in all experimental conditions) allow precise determination of relative load and maximum dynamic strength, and enable coaches and sports scientists to use the different velocity outputs to rapidly and accurately monitor their athletes on a daily basis.

DOI: https://doi.org/10.1519/JSC.0000000000002543

Originally published at:
Loturco, Irineu; Suchomel, Timothy; Kobal, Ronaldo; Arruda, Ademir F S; Guerriero, Aristide; Pereira, Lucas A; Pai, Chi Nan (2018). Force-Velocity Relationship in three Different Variations of Prone Row Exercises. Journal of Strength and Conditioning Research, 33(9):2559-2569.
DOI: https://doi.org/10.1519/JSC.0000000000002543

Improved Performance in Master Runners Competing in the European Championships Between 1978 and 2014

Anaïs L. Schneider,[1] Pantelis T. Nikolaidis,[2] and Beat Knechtle[1,3]

[1]*Institute of Primary Care, University of Zurich, Zurich, Switzerland;* [2]*Exercise Physiology Laboratory, Nikaia, Greece; and* [3]*Medbase St. Gallen Am Vadianplatz, St. Gallen, Switzerland*

Abstract

Schneider, AL, Nikolaidis, PT, and Knechtle, B. Improved performance in master runners competing in the European championships between 1978 and 2014. *J Strength Cond Res* 33(9): 2559–2569, 2019—The performance trends in elite runners have been well investigated, but we have no knowledge about performance trends and the difference between the sexes in elderly runners competing at a high level in varying distances. The purpose of this study was to investigate the performance of these age groups. Data from 17 European Championships held between 1978 and 2014 were analyzed for various race distances (i.e., 100, 200, 400, 800, 1,500, 5,000, 10,000 m, and marathon). Running speed for the top 8 female and male finalists for each age group (35–99 years, split into 5-year gaps) and each race distance were included. A 2-way analysis of variance compared the effects of sex, race distance, age group and calendar year on speed. Subsequent comparisons between race distances, age groups, or calendar years were performed using a post hoc Bonferroni's test. Our analysis shows that men were faster than women in all distances, and the difference between the sexes was greater in the shorter distances. Speed was higher for shorter distances than for longer distances. Younger participants were faster than older ones, and the effect of age group was the largest for the 200 m. There was a minor effect of calendar year on speed in the 100, 20, 1,500, 10,000 m and marathon, and a minor calendar year × sex interaction on running speed was shown for the 200 m. For athletes and coaches, the current study demonstrates that both male and female athletes improved their running performance over time and that the sex gap may have reached its limit.

Key Words speed, runner, sex difference, age group athlete

Address correspondence to Beat Knechtle, beat.knechtle@hispeed.ch.

33(9)/2559–2569

Journal of Strength and Conditioning Research

Introduction

Track and road running is an increasingly popular sports discipline, where participants aim to cover a given distance–usually from 100 m to marathon –as fast as possible (61). The last few years have seen an increase in participation, especially in marathon road running (20,36). Despite the growing participation in running events of varying distances, little is known about the performance trends of elderly female and male elite athletes in track running (48).

Running speed has improved considerably for both women and men during the past 150 years (61). World records in all running events have been continually beaten over the past century (40). Several factors might contribute to the dramatic increase in running performance. In the late 1970s, sports physiology began to be applied to sports training strategies. Different training methods were incorporated, including circuit training, interval training, and sprints. A better understanding of various training components probably played a major role in the increase of performance in the past decades (58). Incorporation of an interval training session has been proven to increase running speed on longer runs and lengthen the time to exhaustion in trained athletes (31). During the past century, studies started to include research about resistance training. The first studies about resistance training started in the 1980s. Since then, it has been shown that resistance training has an impact on neural mechanisms, metabolic adaptations, the cardiovascular system, the endocrine system, connective tissue, and the immune system (32). Changes in training strategies such as an increased training volume helped achieve this progress (51). A greater interest in sport psychology might have helped understanding an athlete's psychological needs to perform better (33). Keegan et al. (24) studied the impact of coaches, parents, and peers on an athlete's motivation and showed that the behavior of the people in an athlete's environment has a direc but complex impact on his or her motivation. Coaching strategies have changed over time and provide athletes with better techniques for coping with anxiety, which can negatively affect athletic performance (42).

Progress in the medical field might also play a role because it provides more concise medical advice in terms of prevention and therapy of sport injuries (58). For example, research about overtraining syndrome in athletes helps understand the etiology of this condition and how to avoid and treat it (6). Radiographic imaging, arthroscopy, and new surgical methods help provide a better, more complete medical support and play a major role in the increase of performance (58). Another contributing factor might be found in the better understanding of the nutritional demands of an athlete's body (58) and of the hydration needed during endurance performance (25). Advances in health technology including the development of functional magnetic resonance imaging have helped understand brain activity during sports (18).

In the past decades, considerable advances have also been made in the field of sports equipment. We now have access to improved design and quality of shoes, clothing, and training equipment. These improvements also helped athletes achieve an increase in sports performance (58). Unfortunately, doping probably also plays a major role in the increase of athletic performance in the past few decades (40). All of these factors and more could play a role in the overall increase of athletic performance.

Men run faster than women. There are several reasons for this difference in endurance performance between the sexes, including higher $\dot{V}O_2max$, lower-body fat percentage (54), larger hearts, higher hemoglobin levels, and greater muscle mass in men (4). Endocrine differences are not to be neglected. Androgens levels are higher in men and contribute to their higher muscle mass (50), which has an impact on neuromuscular performance (12). Although both men and women have improved their running performance, the relative improvement in running performance observed over the

Table 1. Available data for each race distance at the events considered in our study.

			100 m	200 m	400 m	800 m	1,500 m	5,000 m	1,000 m	Marathon
1978	Viareggio	Men	X	X	X	X	X	X	X	X
		Women					X	X		X
1980	Helsinki	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X		X
1982	Strasbourg	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
1984	Brighton	Men	X	X	X	X	X	X	X	
		Women	X	X	X	X	X	X		
1986	Malmö	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
1990	Budapest	Men	X	X	X	X	X	X	X	
		Women								
1994	Athen	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
1996	Malmö	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
1998	Cesenatico	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2000	Jyväskylä	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2002	Potsdam	Men	X	X	X	X	X	X	X	
		Women	X	X	X	X	X	X	X	
2004	Aarhus	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2006	Poznan	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2008	Ljubljana	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2010	Nyiregyháza	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2012	Zittau	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X
2014	Izmir	Men	X	X	X	X	X	X	X	X
		Women	X	X	X	X	X	X	X	X

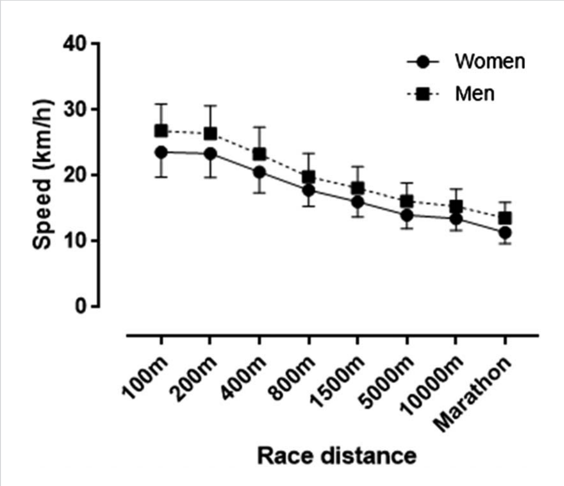

Figure 1. Speed by race distance and sex. Women are depicted by ▲ and men by ●.

past century was greater in female than in male athletes (40). Some findings even suggested that women would outrun men at some point in the future (63,64).

The hypothesis of the narrowing difference between the sexes in running performance has been analyzed by other authors (8,20,53,67). For instance, Zingg et al. (68) showed that female athletes older than 35 years reduced the difference in mountain and city marathons within a decade. In 1922, the difference was approximately 30% and decreased over time, reaching a plateau at 10.7% in 1984, according to Thibault et al. (57). Other authors stated a similar percentage (15,20). Interestingly, one study shows that the difference between the sexes is smaller in ultramarathon running, ranging from 0.2 to 10% (30). The discussion of whether women will catch up to men or whether the difference might be fixed is still ongoing.

Elderly athletes represent a highly active and healthy population with a good quality of life (66). Thus, studies of performance of this athletic elderly population might help to understand the decline in general health with increasing age (66). Aging is generally associated with a decline in both health (39,66) and endurance performance (55). Over the past few decades, however, greater numbers of elderly people have participated in endurance races (22,41,55). In running, elderly athletes have significantly improved their performance between 1975 and 2013 (2).

Regular endurance training, including running, has many health benefits. Several studies demonstrated the benefits of physical activity later in life, such as lower overall mortality (17,62) Lee et al. (35) analyzed the mortality risk of more than 13,000 runners and found out that runners have a lower mortality risk than nonrunners. It has been shown that regular exercise reduces the incidence of cardiovascular and respiratory diseases (44). Couppé et al. found that elderly men who had been practicing endurance running for a long time had lower triglyceride and low-density lipoprotein cholesterol than untrained elderly men (11). The same group analyzed accumulation of advanced glycation end products in the connective tissue and showed that elderly elite athletes have a lower advanced glycation end products accumulation and higher magnetic resonance imaging signal intensity of the patellar tendon, suggesting that endurance training could reduce the age-related deterioration of soft tissues (11). Regular physical exercise has also been shown to improve cognitive function (56).

Based on the existing reports describing other disciplines like swimming (26) where improvement over time was shown for elderly swimmers in all age groups and distances, we might assume similar trends in running; however, we have no knowledge about changes in performance trends in age group track runners over 35 years of age, competing at an elite level in various distances. Such knowledge would be of great value from a theoretical and practical perspective. Sports scientists, especially exercise physiologists, focusing on sex differences would benefit from such knowledge

Table 2. Coefficients (C) and *standard errors of estimate* (*SEE*) from multivariate regression models for race speed of participants by sex and race distance.

	C	*SEE*	*p*
Sex	−3.18	0.08	<0.001
Race distance	−2.06	0.02	<0.001
Interaction sex × race distance	0.17	0.02	<0.001

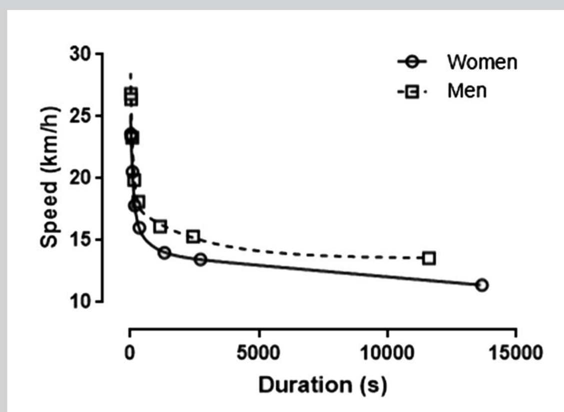

Figure 2. Relationship between speed and race duration for women and men. Women are depicted by ▲ and men by ●.

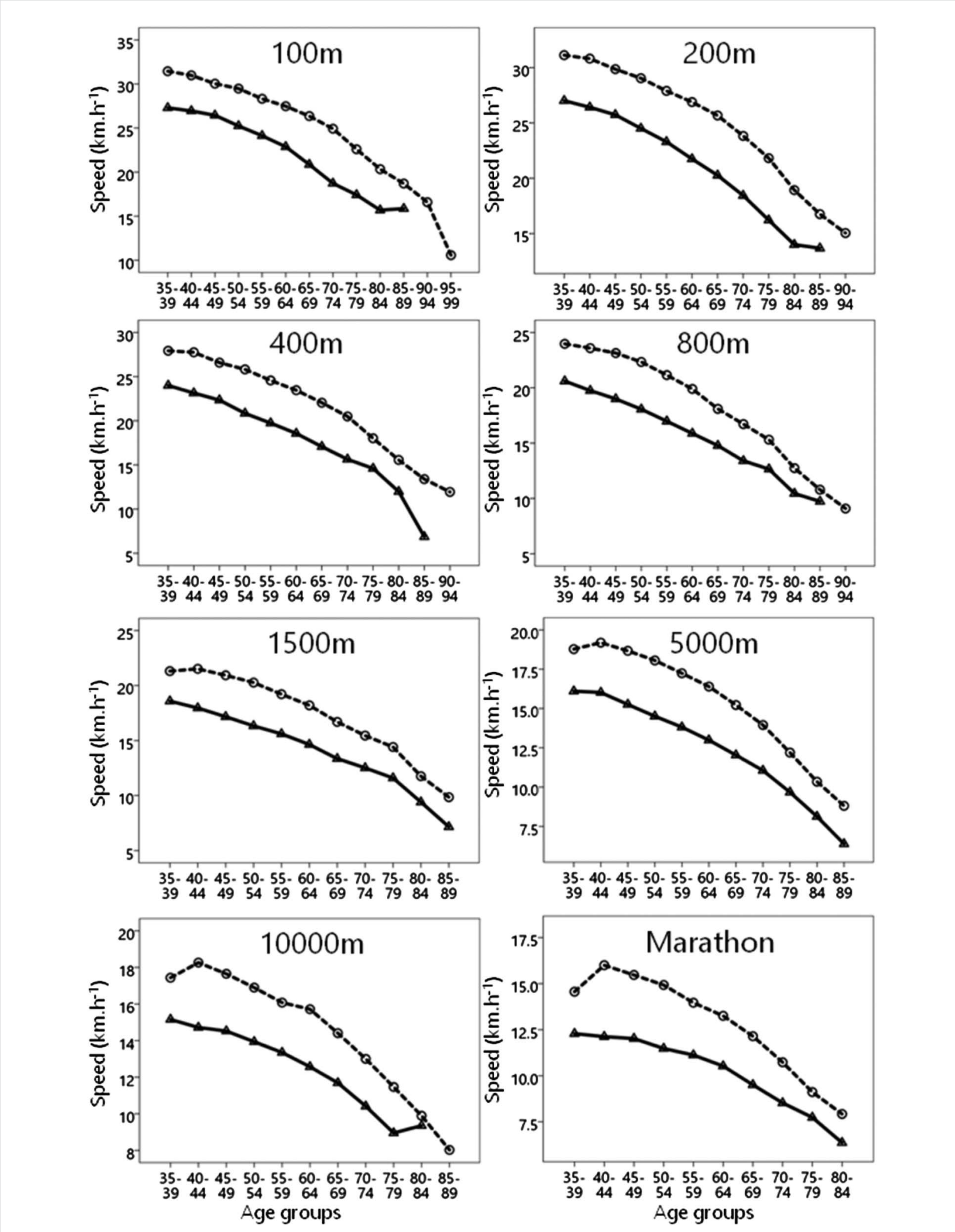

Figure 3. Speed by age group and sex for each race distance. Women are depicted by ▲ and men by ●.

because they would improve their understanding of the evolution of the differences between male and female subjects in sport performance. On the other hand, coaches and fitness trainers working with age group runners from 35 years and onwards might use such information on sex differences to optimize the training of their athletes.

The possibility of a sub-2-hour marathon has been discussed vividly lately. Although runners are getting faster over time, Tucker and Santos-Concejero (59) do not believe in an imminent sub 2-hour marathon because the current average difference between the sexes is approximately 11.2%, and the achievement of a sub 2-hour marathon would represent a 12.9% difference. Another point they bring forward is that the 2.4% required improvement in men's performance is unlikely to happen quickly but rather will take generations to achieve. Hoogkamer et al. (19) did believe a sub 2-hour marathon is achievable and drew a draft of how a lighter shoe, a downhill route, and tailwind might someday reduce the metabolic cost enough to achieve the average velocity of 5.86 $m \cdot s^{-1}$ required for a sub 2-hour marathon.

The first aim of this study was to analyze the performance trends in elite master runners from 1978 until 2014 for 5-year age-group intervals from 35 to 99 years for different race distances (i.e., 100, 200, 400, 800, 1,500, 5,000, 10,000 m, and marathon). The second aim was to analyze the difference between men's and women's running performance. We hypothesized that between 1978 and 2014, both men and women improved their running speed and that the difference between the sexes decreased.

Methods

Experimental Approach to the Problem

To investigate the changes of performance (i.e., running speed) of master athletes across the years along with the difference in performance between men and women, we analyzed the running speed of men and women for different distances. Data from 17 European Championships held between 1978 and 2014 were analyzed for different race distances (i.e., 100, 200, 400, 800, 1,500, 5,000, 10,000 m, and marathon). Only outdoor track races and marathons held on roads were included because of the different events (e.g., 100 vs. 60 m) and conditions (e.g., 400 m in 1 lap vs. 400 m in 2 laps) in outdoor and indoor races, respectively. The youngest athletes in the data set were 35 years old. Reaburn and Dascombe (48) defined master athletes as participants of 35 years or older. We therefore considered athletes older than 35 years to be master athletes and did not include any younger athletes in our study.

Subjects

The European Veterans Athletic Association (EVAA) was founded in 1978 in Italy with the aim to organize European Championships for master athletes and to keep a complete register of the results (http://european-masters-athletics.org/about-us/history.html). We aimed to investigate the results of the European Championships held between 1978 and 2014. The section www.evaa.ch/results.html records the publicly available race results for the years 2000–2014. The result charts for races held between 1978 and 2000 were not available on the Web site, and thus, Ove Edlund, Sweden, provided us with the printed versions for this period. Both the online and the printed race records included results for the distances 100, 200, 400, 800, 1,500, 5,000, 10,000 m, and the marathon. Each athlete was recorded for distance, race time, nationality, and age group. Not every Championships result chart included the competitor's exact age; however, every Championships used the same age groups, where athletes were divided into 5-year age-group intervals as follows: 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, 85–89, 90–94, and 95–99 years. To our knowledge, no subject was excluded from the EVAA data set because of the use of doping. We focused on adult runners only, the age range being 35-97 years old.This study was

Table 3. Coefficients (C) and *standard errors of estimate* (*SEE*) from multivariate regression models for race speed of participants by sex and age group for each race distance.

		C	*SEE*	*p*
100 m	Sex	−4.06	0.18	<0.001
	Age group	−1.19	0.02	<0.001
	Interaction sex × age group	−0.10	0.03	0.001
200 m	Sex	−4.63	0.17	<0.001
	Age group	−1.29	0.02	<0.001
	Interaction sex × age group	−0.02	0.03	0.481
400 m	Sex	−5.21	0.15	<0.001
	Age group	−1.34	0.02	<0.001
	Interaction sex × age group	0.14	0.03	<0.001
800 m	Sex	−4.85	0.13	<0.001
	Age group	−1.24	0.01	<0.001
	Interaction sex × age group	0.23	0.03	<0.001
1,500 m	Sex	−4.37	0.14	<0.001
	Age group	−1.08	0.02	<0.001
	Interaction sex × age group	0.20	0.03	<0.001
5,000 m	Sex	−4.16	0.11	<0.001
	Age group	−0.98	0.01	<0.001
	Interaction sex × age group	0.21	0.02	<0.001
1,000 m	Sex	−4.13	0.15	<0.001
	Age group	−0.91	0.02	<0.001
	Interaction sex × age group	0.27	0.03	<0.001
Marathon	Sex	−4.51	0.18	<0.001
	Age group	−0.82	0.02	<0.001
	Interaction sex × age group	0.35	0.04	<0.001

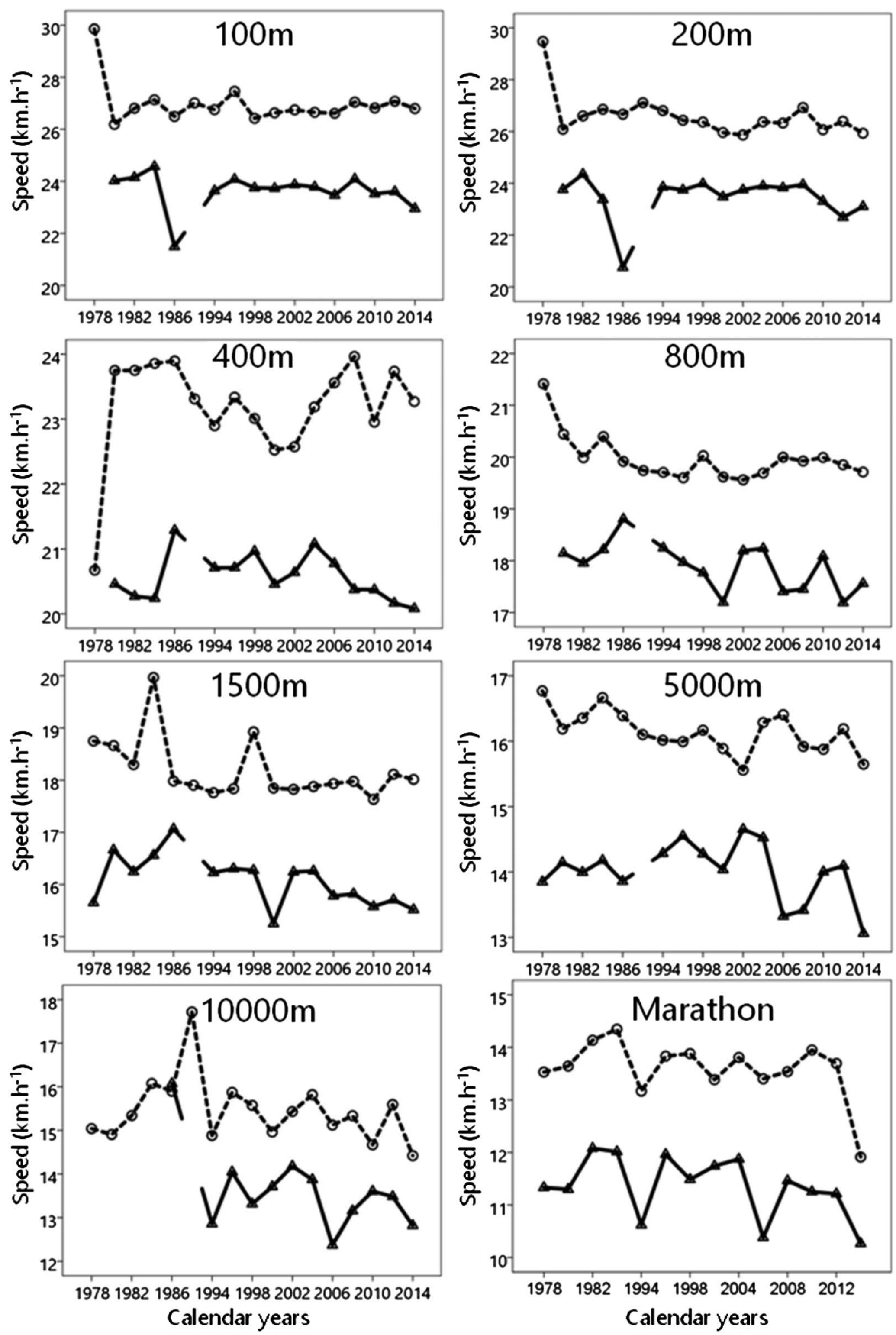

Figure 4. Speed by calendar year and sex for each race distance. Women are depicted by ▲ and men by ●.

approved by the Institutional Review Board of Kanton St. Gallen, Switzerland, with a waiver of the requirement for informed consent of the participants because the study involved the analysis of publicly available data (June 1, 2016).

Procedures

We analyzed the running performance for athletes between 35 and 99 in 5-year age intervals. The race distances included were 100, 200, 400, 800, 1,500, 5,000, 10,000 m, and marathon. Finally, 14,685 race times (6,019 female and 8,666 male times) were included into the data set. The data set is visible in Table 1. For better comparison, we restricted our analysis to the top 8 male and female finishers, as there were different numbers of finishers in each category. Finishers without a recorded race time or who were disqualified for any reason were excluded from our analysis. Running speed was used to compare the performance. As the race times and the distances but not the running speed were listed in the result charts, running speed was calculated in kilometers per hour using the equation, running speed ($km \cdot h^{-1}$) = race distance (m)/race time (sec) $\times$ 3.6.

Statistical Analyses

The statistical software IBM SPSS v.23.0 (SPSS, Chicago, IL, USA) performed all statistical analyses. Mean values and *SD* (*s*) were calculated for all variables. A 2-way analysis of variance (ANOVA) compared effects of sex, race distance, age group, and calendar year on running speed. Subsequent comparisons among race distances, age groups, and calendar years were carried out using post hoc Bonferroni's test. The magnitude of these differences was examined using effect size eta squared (η^2) and evaluated as minor ($0.010 < \eta^2 \leq 0.059$), moderate ($0.059 < \eta^2 \leq 0.138$), and major ($\eta^2 > 0.138$) (9). We analyzed the relationship between speed and race duration using a logarithmic regression model. In addition, we examined the differences in the running speed of men and women using the formula 100 $\times$ (men's running speed $-$ women's running speed)/women's running speed. We also compared variations in running speed by participants' sex, age group, race distance, and calendar year by a mixed-effects regression model. In this model, participants were assigned as random variables, whereas sex, age group, race distance, and calendar year were assigned as fixed variables. We examined interaction effects among these fixed variables. Akaike's information criterion was used to select the final model. These analyses were performed for each race distance separately. A regression analysis of cubic degree was performed between running speed and calendar year, and the coefficient of determination (R^2) was calculated. Statistical significance was set at alpha = 0.05.

Results

Performance by Sex and Race Distance

According to the 2-way ANOVA, a moderate effect of sex on running speed was observed ($p < 0.001$; $\eta^2 = 0.115$), where men were faster than women, as shown in Figure 1. Also, a major effect of race distance on running speed was shown ($p < 0.001$; $\eta^2 = 0.649$), where short distances were faster than longer ones. In addition, a sex $\times$ race distance interaction on running speed was noticed ($p < 0.001$; $\eta^2 = 0.006$) for all distances with the sex difference being greater in the shorter distances. These findings were in agreement with the mixed-effects regression analysis and are shown in Table 2. Figure 2 presents the relationship between running speed and race duration.

Performance by Sex and Age Group

A major effect of sex on running speed ($p < 0.001$), where men were faster than women, was observed for all distances with η^2 ranging from 0.197 (1,000 m) to 0.472 (200 m). Figure 3 represents the difference between the sexes for each distance and each age group. In addition, a major effect of age group on running speed ($p < 0.001$), where the younger groups were faster than the older, was shown for all distances with η^2

Table 4. Coefficients (C) and *standard errors of estimate* (*SEE*) from multivariate regression models for race speed of participants by sex and calendar year for each race distance.

		C	*SEE*	*p*
100 m	Sex	−0.87	33.20	0.979
	Calendar year	0	0.01	0.948
	Interaction sex × calendar year	0	0.02	0.944
200 m	Sex	−58.47	35.01	0.095
	Calendar year	−0.02	0.01	0.161
	Interaction sex × calendar year	0.03	0.02	0.113
400 m	Sex	6.67	34.19	0.845
	Calendar year	−0.01	0.01	0.636
	Interaction sex × calendar year	0	0.02	0.783
800 m	Sex	25.81	29.66	0.384
	Calendar year	−0.01	0.01	0.219
	Interaction sex × calendar year	−0.01	0.01	0.348
1,500 m	Sex	4.77	24.40	0.845
	Calendar year	−0.02	0.01	0.003
	Interaction sex × calendar year	0	0.01	0.779
5,000 m	Sex	−13.03	20.69	0.529
	Calendar year	−0.02	0.01	0.010
	Interaction sex × calendar year	0.01	0.01	0.596
1,000 m	Sex	39.86	35.34	0.260
	Calendar year	−0.02	0.01	0.017
	Interaction sex × calendar year	−0.02	0.02	0.239
Marathon	Sex	−3.69	22.42	0.869
	Calendar year	−0.02	0.01	0.002
	Interaction sex × calendar year	0	0.01	0.946

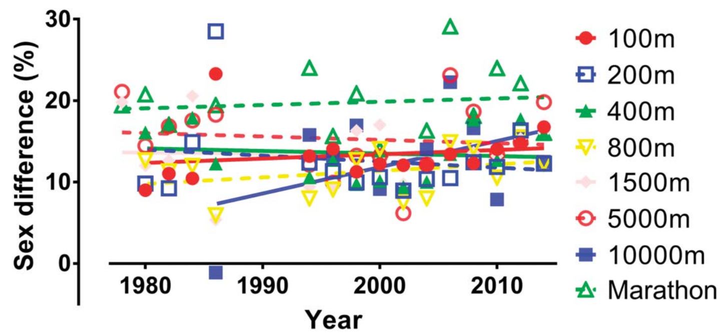

Figure 5. Sex difference in speed by race distance and calendar year.

ranging from 0.474 (marathon) to 0.823 (200 m). A minor sex × age group interaction on running speed ($p < 0.001$), where difference between the sexes was greater in the younger age groups, was noticed for all distances with η^2 ranging from 0.019 (1,500 m) to 0.048 (100 m). The findings of the mixed-effects regression analysis were shown in Table 3.

Performance by Sex Between 1978 and 2014

A minor effect of calendar year on running speed was observed in 100, 200, 1,500, 10,000 m, and marathon ($p \leq 0.044$, $0.014 \leq \eta^2 \leq 0.050$) but not in 400, 800, and 5,000 m ($p \geq 0.160$; $\eta^2 \leq 0.011$) (Figure 4). A small calendar year × sex interaction on running speed ($p = 0.038$; $\eta^2 = 0.013$) was shown for 200 m but not for the rest of the distances. The findings of the mixed-effects regression analysis were presented in Table 3. The regression analysis of cubic degree between sex difference and calendar year showed variation by race distance: 100 m ($R^2 = 0.41$), 200 m ($R^2 = 0.34$), 400 m ($R^2 = 0.628$), 800 m ($R^2 = 0.309$), 1,500 m ($R^2 = 0.209$), 5,000 m ($R^2 = 0.328$), 10,000 m ($R^2 = 0.489$), and marathon ($R^2 = 0.046$). These findings are shown in Table 4 and Figure 5.

Discussion

The main findings of the present study were that (a) men were faster than women in all distances, (b) the difference between men and women in running speed was greater in the shorter distances, with the greatest difference in 200 m and the smallest in 10,000 m, (c) running speed was faster for shorter distances than for longer distances, (d) younger participants were faster than older ones, (e) the effect of age was largest for the 200 m distance and the smallest for the marathon, (f) there was a minor effect of calendar year on running speed in 100, 200, 1,500, 10,000 m, and marathon, and (g) a minor calendar year × sex interaction in running speed was shown for 200 m.

The first result was that men were faster than women for all distances and age groups, which was supported by other studies (20,53). Generally speaking, the difference of 10–12% between male and female running speeds has been consistent for both shorter and longer distances (15).

Although one might argue that this result was trivial, recent studies investigating master pool swimmers in freestyle (26), breaststroke (28), backstroke (60), and open-water swimmers (27) showed that men were faster than women for younger age groups but not for older age groups where women achieved a similar performance to men. The explanation was that in the studies with swimmers at the World Championships, no selection by age group occurred, and all swimmers in all age groups were considered. The men-to-women ratio changed across age groups and, therefore, explains the fact that women were able to achieve a similar performance to men in the older age groups.

Men were faster than women in our study. This may be because of their lower-body fat percentage and their higher $\dot{V}O_2max$ (54) compared with women. However, these hypotheses were limited, as we did not perform any determinations of body fat or $\dot{V}O_2max$. Men also seem to be more competitive (13) and more willing to commit to a high-intensity training program (15) than women. There might also be a historical component because it is known that women have been participating in official races for a shorter period and have therefore less experience in running races (20). We did not collect any historical data ourselves, but it is known that the first modern Olympic Games were introduced in 1896 with only male athletes, and a century later (in 1984), female runners were first included for the marathon distance (58).

There are other differences between male and female runners. Women tend to have a more even pace throughout a race, whereas men slow down for the second half of the marathon (14). This difference might be the result of different choices while racing or to the fact that men are depleting their muscle glycogen more rapidly than women (14).

In the present study, we used running as a way to compare male and female performance and the changes over time. Distance running is a suitable discipline to compare male and female performance because it is objective, open to everyone who wants to participate, and popular among men and women (13). Sex differences in endurance performance were also found in other athletic disciplines. In swimming races, the sex differences seem more important in elderly than in younger swimmers, although not as important as in marathon running (52).

A second important discovery was that the difference in male and female running speed was greater for shorter distances and smaller for longer distances. The effect of sex was the highest for the 200-m distance and the smallest for the 10,000-m distance. Sprint performance depends on peak power output, which increases linearly with the amount of lean mass in the lower extremities and is higher in males (45). Proportionally, women oxidize more fat than men during endurance exercise (7), which might help explain why women are less fatigued on longer distances (8). Other contributing factors to fatigue could be hormonal differences, as estrogens are known to have a protective role in exercise-related muscle damage that accompanies longer aerobic exercise (65).

Another discovery was that running speed was faster for shorter distances than for longer ones. This result was expected and has been demonstrated by other authors. For example, Weiss et al. (61) showed that running speed decreased with increasing race distance. Different physiological factors cause a reduction in physical effort, including cardiorespiratory capacity, $\dot{V}O_2max$, and muscle fatigue (23).

Another important result was that younger competitors ran faster than elderly athletes for every distance. This effect of age on running speed was expected and has been demonstrated by other authors (10,20,29,55).

The best running times are often achieved by the age of 35 years with a small and linear decline until approximately 50–60 years of age, with a more pronounced decline after that (55). A decline in $\dot{V}O_2$ (which is because of a reduction in cardiac output) an increase in body fat percentage, a reduction in peripheral oxygen extraction, and most importantly, a reduction in muscle mass (47) seem to play an important role in the decline of running performance in elderly athletes (46). Younger master athletes have higher muscle mass and a greater number of motor units than older master athletes (16). Muscle atrophy causes a reduction of muscle mass (1,3). Muscle atrophy in turn could partially be explained by neuronal dysfunction (5). Therefore, the age-related muscle loss contributes to the reduction of $\dot{V}O_2max$ (47), which in turn plays an important role in the age-related decrease of running speed (46).

The oldest competitors in our study were 97 years old, but other authors reported great sports performance of centenarians (37), showing that physical activity is possible until late in life. Age-related sarcopenia could also play a role in the performance decline. Sarcopenia is defined by a decrease in the number and function of muscle fibers. It is the result of various factors including age-related defect in autophagy resulting in protein accumulation, impaired mitochondrial function because of increased reactive oxygen species, diminished regenerative potential of muscle fibers, degenerative atrophy, vitamin deficiencies, and hormonal changes. Muscle mass and strength are also linked to testosterone levels. An increase in age correlates to decreased testosterone levels in both men and women, which is linked to a decrease in muscle mass, particularly in men (43).

Another finding was that the age-associated decline in performance was the largest for the 200-m distance and the smallest for the marathon. There are divergent results in the current literature. Rittweger et al. (49) showed that the age-related decrease in running performance was similar for both sprint and long-distance runners. Drey et al. (16) compared the skeletal muscle mass in power- and endurance-trained master athletes competing in the 2012 European Championship held in Zittau, Germany. Power-trained master athletes had a better muscle mass than endurance-trained master athletes (16). During the aging process, relatively more type II muscle fibers are lost (38). This could explain why in our study, the age-related decline was more pronounced for the 200-m distance and smallest for the marathon. Both sprinting and long-distance training are beneficial during the aging process (34). The fact that 99-year-old athletes were competing in Championships shows that aging might come with a decrease in running performance, but it is compatible with an active lifestyle.

Another important discovery was an effect of calendar year on running speed for most distances. It has been suggested by different authors that running performance has been improving over the years (55,61). World records in athletic sports like running have dramatically increased over the past century. The improvements in race times were directly proportional to race distances, meaning the smallest improvements were achieved on short distances like 100 m and the largest improvements were observed in longer distances such as marathon running (40). Weiss et al. (61) showed that the improvement observed at the beginning of the century is now stagnating.

The last significant finding was that the difference between the sexes has decreased over the years but only for the 200-m distance. We expected that the difference would be decreasing for every distance; however, results of earlier studies were divergent. Thibault et al. (57) showed that the difference has been stable since 1984 and that the gap will most likely not be closed. Hunter et al. (21) showed that the difference diminished between 1980 and 2010. The researchers also claimed that the male-female difference is closely linked to the male-female participation ratio, and therefore, many studies have a historical and sampling bias (20).

A limitation of these discoveries was that the present study focused on European athletes and outdoor Championships. Thus, caution was needed to generalize these findings to non-European athletes and indoor Championships. Non-Europeans showed superior performance in athletic running events, and their performance would be expected to vary differently by calendar year and sex. Moreover, some events differed between outdoor and indoor competitions (e.g., 100 vs. 60 m, 5,000 vs. 3000 m, respectively) or do not exist in indoors competitions (10,000 m and marathon) and those which existed in both competitions (e.g., 400 m) included different numbers of laps (e.g., 1 vs. 2) affecting the physiological, technical, and tactical demands of a similar distance. Nevertheless, the strength of the study was its novelty because it is the first one in this topic, adding novel information about the variation of performance of master runners by calendar year and sex.

In conclusion, male runners are generally faster than females. The gap between male and female endurance performance has been decreasing over the past decades but that it seems to have reached a limit. In general, all athletes are getting faster over time.

Practical Applications

For athletes and coaches, information acquired through this study could have practical implications for practitioners working with master runners; most training programs were developed and applied originally in men, and, thus, knowledge about sex differences would help coaches designing tailored training programs for women, as well. In addition to this practical application, the results about the variation of performance by age group and the variation of the effect of age by race distance would be of interest for researchers studying master athletes as a model of effective aging and for sports scientists, especially exercise physiologists, focusing on sex differences in sport performance.

Acknowledgments

The authors thank Ove Edlund, Sweden, for providing us the data before the year 2000 and Mrs. Knechtle for transcribing this data set. The authors also thank Patricia Villiger for her help in translation.

References

1. Akima, H, Kano, Y, Enomoto, Y, Ishizu, M, Okada, M, Oishi, Y, Katsuta, S, and Kuno, S. Muscle function in 164 men and women aged 20–84 yr. *Med Sci Sports Exerc* 33: 220–226, 2001.
2. Akkari, A, Machin, D, and Tanaka, H. Greater progression of athletic performance in older Masters athletes. *Age Ageing* 44: 683–686, 2015.
3. Brooks, SV and Faulkner, JA. Skeletal muscle weakness in old age: Underlying mechanisms. *Med Sci Sports Exerc* 26: 432–439, 1994.
4. Brown, N and Scurr, J. Do women with smaller breasts perform better in long-distance running? *Eur J Sport Sci* 16: 965–971, 2016.
5. Campbell, MJ, McComas, AJ, and Petito, F. Physiological changes in ageing muscles. *J Neurol Neurosurg Psychiatry* 36: 174–182, 1973.
6. Carfagno, DG and Hendrix, JC III. Overtraining syndrome in the athlete: Current clinical practice. *Curr Sports Med Rep* 13: 45–51, 2014.
7. Carter, SL, Rennie, C, and Tarnopolsky, MA. Substrate utilization during endurance exercise in men and women after endurance training. *Am J Physiol Endocrinol Metab* 280: E898–E907, 2001.
8. Coast, JR, Blevins, JS, and Wilson, BA. Do gender differences in running performance disappear with distance? *Can J Appl Physiol* 29: 139–145, 2004.
9. Cohen, J. The Analysis of Variance and Covariance. In: *Statistical Power Analysis for the Behavioral Sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates, 1988. pp. 273–406.
10. Connick, MJ, Beckman, EM, and Tweedy, SM. Relative age affects marathon performance in male and female athletes. *J Sports Sci Med* 14: 669–674, 2015.
11. Couppe, C, Svensson, RB, Grosset, JF, Kovanen, V, Nielsen, RH, Olsen, MR, Larsen, JO, Praet, SF, Skovgaard, D, Hansen, M, Aagaard, P, Kjaer, M, and Magnusson, SP. Life-long endurance running is associated with reduced glycation and mechanical stress in connective tissue. *Age (Dordr)* 36: 9665, 2014.
12. Crewther, BT, Cook, C, Cardinale, M, Weatherby, RP, and Lowe, T. Two emerging concepts for elite athletes: The short-term effects of testosterone and cortisol on the neuromuscular system and the dose-response training role of these endogenous hormones. *Sports Med* 41: 103–123, 2011.
13. Deaner, RO. Distance running as an ideal domain for showing a sex difference in competitiveness. *Arch Sex Behav* 42: 413–428, 2013.
14. Deaner, RO, Addona, V, Carter, RE, Joyner, MJ, and Hunter, SK. Fast men slow more than fast women in a 10 kilometer road race. *PeerJ* 4: e2235, 2016.
15. Deaner, RO and Mitchell, D. More men run relatively fast in U.S. road races, 1981–2006: A stable sex difference in non-elite runners. *Evol Psychol* 9: 600–621, 2011.
16. Drey, M, Sieber, CC, Degens, H, McPhee, J, Korhonen, MT, Müller, K, Ganse, B, and Rittweger, J. Relation between muscle mass, motor units and type of training in master athletes. *Clin Physiol Funct Imaging* 36: 70–76, 2016.
17. Ekelund, U, Steene-Johannessen, J, Brown, WJ, Fagerland, MW, Owen, N, Powell, KE, Bauman, A, and Lee, IM. Does physical activity attenuate, or even eliminate, the detrimental association of sitting time with mortality? A harmonised meta-analysis of data from more than 1 million men and women. *Lancet* 388: 1302–1310, 2016.
18. Holmes, PS and Wright, DJ. Motor cognition and neuroscience in sport psychology. *Curr Opin Psychol* 16: 43–47, 2017.
19. Hoogkamer, W, Kram, R, and Arellano, CJ. How biomechanical improvements in running economy could break the 2-hour marathon barrier. *Sports Med* 47: 1739–1750, 2017.
20. Hunter, SK and Stevens, AA. Sex differences in marathon running with advanced age: Physiology or participation? *Med Sci Sports Exerc* 45: 148–156, 2013.
21. Hunter, SK, Stevens, AA, Magennis, K, Skelton, KW, and Fauth, M. Is there a sex difference in the age of elite marathon runners? *Med Sci Sports Exerc* 43: 656–664, 2011.
22. Jokl, P, Sethi, PM, and Cooper, AJ. Master's performance in the New York city marathon 1983–1999. *Br J Sports Med* 38: 408–412, 2004.
23. Kayser, B. Exercise starts and ends in the brain. *Eur J Appl Physiol* 90: 411–419, 2003.
24. Keegan, R, Harwood, C, Spray, C, and Lavallee, D. A Qualitative Investigation of the Motivational Climate in Elite Sport. *Psychology of Sport and Exercise* 15; 97–107, 2014.
25. Kenefick, RW and Cheuvront, SN. Hydration for recreational sport and physical activity. *Nutr Rev* 70(Suppl 2): S137–S142, 2012.
26. Knechtle, B, Nikolaidis, PT, König, S, Rosemann, T, and Rüst, CA. Performance trends in master freestyle swimmers aged 25–89 years at the FINA World Championships from 1986 to 2014. *Age* 38: 1–8, 2016.
27. Knechtle, B, Nikolaidis, PT, Rosemann, T, and Rüst, CA. Performance trends in 3000 m open-water age group swimmers from 25 to 89 years competing in the FINA World Championships from 1992 to 2014. *Res Sports Med* 25: 67–77, 2017.
28. Knechtle, B, Nikolaidis, PT, Rosemann, T, and Rust, CA. Performance trends in age group breaststroke swimmers in the FINA World Championships 1986–2014. *Chin J Physiol* 59: 247–259, 2016.
29. Knechtle, B, Rust, CA, Rosemann, T, and Lepers, R. Age-related changes in 100-km ultra-marathon running performance. *Age (Dord)* 34: 1033–1045, 2012.
30. Knechtle, B, Valeri, F, Nikolaidis, P, Zingg, M, Rosemann, T, and Rüst, C. Do women reduce the gap to men in ultra-marathon running? *Springerplus* 5: 672, 2016.

31. Koral, J, Oranchuk, DJ, Herrera, R, and Millet, GY. Six sessions of sprint interval training improves running performance in trained athletes. *J Strength Cond Res* 32: 617–623, 2018.
32. Kraemer, WJ, Ratamess, NA, Flanagan, SD, Shurley, JP, Todd, JS, and Todd, TC. Understanding the science of resistance training: An evolutionary perspective. *Sports Med* 47: 2415–2435, 2017.
33. Kremer, J and Moran, A. Swifter, higher, stronger: The history of sport psychology. *Psychologist* 21: 740–742, 2008.
34. Kusy, K and Zieliński, J. Sprinters versus long-distance runners: How to grow old healthy. *Exerc Sport Sci Rev* 43: 57–64, 2015.
35. Lee, DC, Pate, RR, Lavie, CJ, Sui, X, Church, TS, and Blair, SN. Leisure-time running reduces all-cause and cardiovascular mortality risk. *J Am Coll Cardiol* 64: 472–481, 2014.
36. Lepers, R and Cattagni, T. Do older athletes reach limits in their performance during marathon running? *Age (Dordr)* 34: 773–781, 2012.
37. Lepers, R, Stapley, PJ, and Cattagni, T. Centenarian athletes: Examples of ultimate human performance? *Age Ageing* 45: 729–733, 2016.
38. Lexell, J. Human aging, muscle mass, and fiber type composition. *J Gerontol A Biol Sci Med Sci* 50: 11–16, 1995.
39. Leyk, D, Erley, O, Ridder, D, Leurs, M, Ruther, T, Wunderlich, M, Sievert, A, Baum, K, and Essfeld, D. Age-related changes in marathon and half-marathon performances. *Int J Sports Med* 28: 513–517, 2007.
40. Lippi, G, Banfi, G, Favaloro, EJ, Rittweger, J, and Maffulli, N. Updates on improvement of human athletic performance: Focus on world records in athletics. *Br Med Bull* 87: 7–15, 2008.
41. Mohlenkamp, S, Lehmann, N, Breuckmann, F, Brocker-Preuss, M, Nassenstein, K, Halle, M, Budde, T, Mann, K, Barkhausen, J, Heusch, G, Jockel, KH, and Erbel, R. Running: The risk of coronary events: Prevalence and prognostic relevance of coronary atherosclerosis in marathon runners. *Eur Heart J* 29: 1903–1910, 2008.
42. Mottaghi, M, Atarodi, A, and Rohani, Z. The relationship between coaches' and athletes' competitive anxiety, and their performance. *Iran J Psychiatry Behav Sci* 7: 68–76, 2013.
43. Naranjo, JD, Dziki, JL, and Badylak, SF. Regenerative medicine approaches for age-related muscle loss and sarcopenia: A mini-Review. *Gerontology* 63: 580–589, 2017.
44. Paffenbarger, RS Jr, Hyde, RT, Wing, AL, and Hsieh, CC. Physical activity, all-cause mortality, and longevity of college alumni. *N Engl J Med* 314: 605–613, 1986.
45. Perez-Gomez, J, Rodriguez, GV, Ara, I, Olmedillas, H, Chavarren, J, Gonzâlez-Henriquez, JJ, Dorado, C, Calbet, JA. Role of muscle mass on sprint performance: Gender differences?. *Eur J Appl Physiol* 103: 375, 2008.
46. Pollock, ML, Foster, C, Knapp, D, Rod, JL, and Schmidt, DH. Effect of age and training on aerobic capacity and body composition of master athletes. *J Appl Physiol* 62: 725–731, 1987.
47. Proctor, DN and Joyner, MJ. Skeletal muscle mass and the reduction of V̇O2max in trained older subjects. *J Appl Physiol* 82: 1411–1415, 1997.
48. Reaburn, P and Dascombe, B. Anaerobic performance in masters athletes. *Eur Rev Aging Phys Activity* 6: 39–53, 2009.
49. Rittweger, J, Di Prampero, PE, Maffulli, N, and Narici, MV. Sprint and endurance power and ageing: An analysis of master athletic world records. *Proc Biol Sci* 276: 683–689, 2009.
50. Rossetti, ML, Steiner, JL, and Gordon, BS. Androgen-mediated regulation of skeletal muscle protein balance. *Mol Cellular Endocrinol* 447: 35–44, 2017.
51. Salinero, JJ, Soriano, ML, Lara, B, Gallo-Salazar, C, Areces, F, Ruiz-Vicente, D, Abian-Vicen, J, Gonzalez-Millan, C, and Del Coso, J. Predicting race time in male amateur marathon runners. *J Sports Med Phys Fitness* 57: 1169–117, 2016.
52. Senefeld, J, Joyner, MJ, Stevens, A, and Hunter, SK. Sex differences in elite swimming with advanced age are less than marathon running. *Scand J Med Sci Sports* 26: 17–28, 2016.
53. Senefeld, J, Smith, C, and Hunter, SK. Sex differences in participation, performance, and age of ultramarathon runners. *Int J Sports Physiol Perform* 11: 635–642, 2016.
54. Sparling, PB and Cureton, KJ. Biological determinants of the sex difference in 12-min run performance. *Med Sci Sports Exerc* 15: 218–223, 1983.
55. Tanaka, H and Seals, DR. Endurance exercise performance in masters athletes: Age-associated changes and underlying physiological mechanisms. *J Physiol* 586: 55–63, 2008.
56. Tarumi, T, Gonzales, MM, Fallow, B, Nualnim, N, Lee, J, Pyron, M, Tanaka, H, and Haley, AP. Cerebral/peripheral vascular reactivity and neurocognition in middle-age athletes. *Med Sci Sports Exerc* 47: 2595–2603, 2015.
57. Thibault, V, Guillaume, M, Berthelot, G, Helou, NE, Schaal, K, Quinquis, L, Nassif, H, Tafflet, M, Escolano, S, Hermine, O, and Toussaint, JF. Women and men in sport performance: The gender gap has not evolved since 1983. *J Sports Sci Med* 9: 214–223, 2010.
58. Tipton, CM. Sports medicine: A century of progress. *J Nutr* 127: 878s–885s, 1997.
59. Tucker, R and Santos-Concejero, J. An imminent sub 2-hours marathon is unlikely: Historical trends of the gender gap in running events. *Int J Sports Physiol Perform* 12: 1107–1022, 2016.
60. Unterweger, CM, Knechtle, B, Nikolaidis, PT, Rosemann, T, and Rust, CA. Increased participation and improved performance in age group backstroke master swimmers from 25–29 to 100–104 years at the FINA World Masters Championships from 1986 to 2014. *Springerplus* 5: 645, 2016.
61. Weiss, M, Newman, A, Whitmore, C, and Weiss, S. One hundred and fifty years of sprint and distance running - past trends and future prospects. *Eur J Sport Sci* 16: 393–401, 2016.
62. Wen, CP, Wai, JP, Tsai, MK, Yang, YC, Cheng, TY, Lee, MC, Chan, HT, Tsao, CK, Tsai, SP, and Wu, X. Minimum amount of physical activity for reduced mortality and extended life expectancy: A prospective cohort study. *Lancet* 378: 1244–1253, 2011.
63. Whipp, BJ and Ward, SA. Will women soon outrun men? *Nature* 355: 25, 1992.
64. Whyte, G. Age, sex and (the) race: Gender and geriatrics in the ultra-endurance age. *Extrem Physiol Med* 3: 1, 2014.
65. Williams, T, Walz, E, Lane, AR, Pebole, M, and Hackney, AC. The effect of estrogen on muscle damage biomarkers following prolonged aerobic exercise in eumenorrheic women. *Biol Sport* 32: 193–198, 2015.
66. Wright, VJ and Perricelli, BC. Age-related rates of decline in performance among elite senior athletes. *Am J Sports Med* 36: 443–450, 2008.
67. Zingg, MA, Karner-Rezek, K, Rosemann, T, Knechtle, B, Lepers, R, and Rust, CA. Will women outrun men in ultra-marathon road races from 50 km to 1,000 km? *Springerplus* 3: 97, 2014.
68. Zingg, MA, Knechtle, B, Rust, CA, Rosemann, T, and Lepers, R. Reduced performance difference between sexes in master mountain and city marathon running. *Int J Gen Med* 6: 267–275, 2013.